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REPORT NO. 951

THE MACH-DVOŘÁK PHENOMENON AND BINOCULAR FUSION OF MOVING STIMULI

(Interim Report)

by

George S. Harker, Ph.D.

30 November 1971

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UNITED STATES ARMY
MEDICAL RESEARCH AND DEVELOPMENT COMMAND

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ACKNOWLEDGMENT

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13. ABSTRACT

Depth judgments of the Mach-Dvořák phenomenon induced by cyclic, intermittent stimulation were used to assess eye coordination in binocular vision. The response to the experimental manipulations of the simultaneous and alternate neutral points, the points of zero and maximum disparity, was suggestive of the function of multiple neural processes. The data were strongly supportive of an interaction between direction of stimulus motion and interocular sequencing. Reduced illumination of one eye affected the time of occurrence of the simultaneous and alternate neutral points oppositely, dependent upon exposure conditions. The data for equal duration exposure condition were suggestive of the known nasal-temporal conductive latency difference.

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ABSTRACT

THE MACH-DVOŘÁK PHENOMENON AND BINOCULAR FUSION OF MOVING STIMULI

OBJECTIVE

To document with moving stimuli and intermittent exposure, the occurrence of the fusion referent in binocular vision and to observe its response to illumination level, duration of exposure, direction of motion, and stimulated eye.

METHOD

The procedure of the Mach-Dvořák phenomenon was employed with unequal stimulation of the two eyes. The exposure to one eye was short, and held constant as an index, while the other was varied to encompass the experimental manipulations. The short index exposure was adjusted in delay to mark the occurrence of points of no perceived depth between upper and lower portions of the display which moved in laterally opposed directions. Stimulation of the two eyes was cyclic at 9.1 cps. The experimental manipulations were presented in discrete combinations in a procedure patterned after the double random staircase of Cornsweet (13). The observer's response was a depth judgment. Graphic records were read to provide measures of the time of occurrence within the cyclic interval of simultaneous and alternate neutral points.

SUMMARY

Analysis of the obtained delay measures indicated a complex relation of the fusion referent to the experimental variables. The depth perceived varied uniquely with the direction of motion of the stimulus and the eye stimulated. In part, this interaction seemed to be the result of the known nasal-temporal retinal-cortical conduction time difference. The change of the obtained measures with exposure duration and peak luminance suggested the presence of multiple, interactive processes as determining the occurrence of the fusion referent rather than a time-locked function.

CONCLUSIONS

1. Manipulation of the relative, interocular exposure duration demonstrated a progression from eye sequence with equal exposures to "the short exposure precedes the long exposure" with unequal exposures as the determiner of the relative depth perceived. Conceivably, the neural characteristics operative in determining the effective eye sequence of short

and long exposures are also effective in eye sequencing when the exposures are equal.

2. The simultaneous and alternate neutral points (though their occurrence is concomitant to the cyclic nature of the stimulation), were not conjugate in their response to the experimental manipulations. Both neutral points were responsive to exposure duration, albeit to a different degree, and in a manner suggestive of the operation of multiple fusional processes.

3. Manipulation of the luminance level viewed by the referent eye, to reverse the direction of the concomitant interocular illumination difference, produced changes both consistent and inconsistent with the conduction latency explanation offered for the Pulfrich phenomenon. The physical upper limit of perceived depth with manipulation of exposure duration was consistent with that obtained with Δ log I differences alone and evidenced no discontinuity as the limit of intermittence was approached.

4. Evidence for a time-locked fusion referent was not obtained. Rather, the data indicated a complex interrelation of several possible experimental manipulations in determining the time of occurrence of the fusion referent.

5. Nasal-temporal conduction time differences seem to be clearly evident in a post hoc divergent-convergent categorization of the obtained data.

6. Simple additivity of the disparities from interocular illumination difference and intermittence was not demonstrated. Rather, the manipulation of intermittence and luminance produced interactive effects. Thus, the latency explanation of Pulfrich is not directly generalizable to Mach-Dvořák; however, no barrier is offered by the obtained data to the generalization of an explanation of the Mach-Dvořák to the Pulfrich phenomenon.

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THE MACH-DVOŘÁK PHENOMENON AND BINOCULAR FUSION OF MOVING STIMULI

INTRODUCTION

History. In 1872 Mach presented a paper by Dvořák to the Bohemian Royal Society of Sciences which described a collection of demonstrations developed in the laboratory at Prague. The central theme of the paper was timing relations in the perceptual process, particularly as they might be said to characterize a "personal time difference." The demonstration from which the current work stems involved the binocular view of a moving stimulus through a large episcotister disc with equal apertures at two radii which differed by the interocular distance. The apertures were angularly displaced one from the other to provide for sequential stimulation. The sequence and delay between the view with each eye was controlled by the angular displacement of the apertures and the direction and speed of rotation of the episcotister. With fusion of the sequential views of the moving stimulus, the path of stimulus motion was perceived to be displaced in depth toward or away from the observer. The direction of displacement was dependent upon the direction of stimulus motion and the order of the eye views. Separate efforts were made by Sanford (1) and Münsterberg (2) to provide a more effective apparatus to produce the phenomenon, yet no systematic study found its way into the literature.

The explanation offered by Dvořák for the observed depth displacement assumed that a point a of the moving stimulus was presented momentarily to one eye and subsequently (delayed by the sequencing of the apertures), to the other eye, the point a having moved laterally to a new position a'. The neural representations, a and a', though sequential in time are perceived as simultaneous, and the displacement of the point a with respect to fixed stimulation gives rise to stereoscopic disparity in the binocular view. In essence, neglecting the role of intermittence, this is the explanation given by Fertsch for the Pulfrich phenomenon 50 years later (3-6).

Fusion Referent. The author has suggested that the Mach-Dvořák phenomenon mediated by asymmetrical suppression of vision in the two eyes and intermittence of the neural excitation might be evoked as an explanation of the Pulfrich phenomenon (7). The formulation specified that the eyes would initiate viewing simultaneously and terminate viewing sequentially, the filtered eye first and the unfiltered eye second. This explanation specifically requires that the points a and a' occur with the termination of viewing in the individual eye. Should they occur with the initiation of viewing there would be no disparity due to movement of the physical stimulus.

Concern for the specifics of "fusion" is not restricted to the suppression explanation of the Pulfrich phenomenon. The latency explanation has similar problems. Clearly, if simultaneous exposure to the two eyes of a moving stimulus is sufficiently short, retinal movement will not occur and there can be no cortical disparity despite visual latency differences (8). Conversely, with continuous viewing, cortical disparity can only occur between the excitation from retinally disparate points. Thus, the mechanism of fusion must respond to timing relations within the neural representation such that sequential stimulation of displaced retinal points is selectively converted to simultaneous stimulation and cortical disparity. Visual latency as an explanatory mechanism implies that the neural representation is equivalent for both eyes, though delayed for one. Differential suppression as an explanatory mechanism assumes that the neural representations are not equivalent, specifically that they differ in their time of termination. In each instance, "fusion" is the combination in a single time frame of equivalent neural features from disparate retinal elements. The ability to identify the points a and a', the equivalent neural feature, or the "fusion contour" would facilitate evaluation of these and other possible explanatory mechanisms as well as the interrelation of phenomena.

EXPERIMENTAL

An Approach. The intermittent stimulation of the Mach-Dvořák phenomenon offers a potential mechanism for such a determination. If, in addition to manipulation of the sequential delay, the exposure to one eye is held constant as an index, the exposure to the other eye could be varied to ask the question, "When in the stimulation from an extended view of the moving stimulus does the referent for fusion occur?" (6,9). Potentially, fusion could be referred to the onset, the offset, or to some intermediate point in the exposure interval. These possibilities could be treated as one in the constant index exposure if it were short. The exposure could then be delayed in time to mark the occurrence of the fusion referent--point of no perceived depth displacement--in longer exposures to the other eye. If delay of the index exposure is measured from the onset of the experimental exposure, changes in delay will directly reflect changes in the time of occurrence of the fusion referent.

Since multiple exposures of the moving stimulus are an integral part of the Mach-Dvořák phenomenon, a cyclic restriction is imposed upon the disparities which can be developed by delay of the index with respect to the experimental exposure. The neutral point, point of no perceived depth displacement, associated with both eyes viewing together for a time (simultaneous neutral point) should mark the reduction to zero of the effective disparity between the fusion referent of the experimental and index exposures. The relative depth perceived as this point is approached is such that (right eye before the left eye) rotation of a pendulum would be counterclock and vice versa (1,3,6,7). Continued increase of delay, either positive or negative from the simultaneous neutral point, should result in a second neutral point as the fusion referent shifts to the next cycle of exposures and the physical pre-conditions for the simultaneous neutral point are reestablished. Potentially, the disparity will increase to some maximum at which delay the sequential eye-order would reverse and further increase be effectively a decrease of delay in the opposite time order. This shift would take place characteristically during the interval when the sequential exposures of the moving stimulus do not overlap and the eyes are viewing alternately (alternate neutral point).

Work with intermittent binocular views of a moving stimulus indicates that the depth perceived is sensitive to sequential delay, exposure duration, cyclic interval, luminance, and stimulus velocity. The depth relations perceived reverse both with the direction of stimulus motion and the order of viewing with the two eyes. Apparently, the perceived depth relations can be an indicator of both the effective order and magnitude of the induced cortical disparity.

Apparatus. The viewing situation (Figure 1) consisted of an observer's position and the visual stimulus spaced 3 meters apart. The observer's position provided an adjustable chin support and 1 cm diameter apertures adjustable to the observer's interpupillary distance. These apertures were equipped with filter holders and were independently shuttered by rotary occluders driven by stepping motors. Immediately beyond the apertures--in the line of sight from the observer to the stimulus--a partial mirror reflected background luminance of 6.5 mL into the field of view. This illumination was provided by a diffusion surface of milk lucite mounted 36 cm from the plane of the apertures. Both the mirror and the diffusion surface were of a size to extend beyond the binocular field of view available through the apertures (approximately 18.5°). A large, manually operated shutter permitted the experimenter to occlude the visual stimuli from the observer.

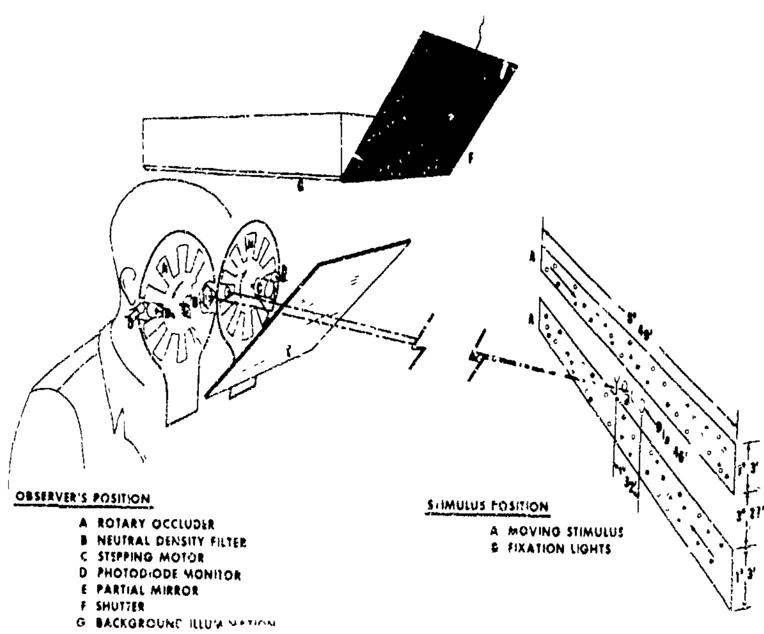

Fig. 1. Schematic of observer and stimulus positions, principal components, and angular subtenses of the visual stimuli.

The visual stimulus consisted of two bands of moving, transillum-inated figures and a fixed configuration of four horizontally displaced lights. The intent was to provide simultaneously both left-to-right and right-to-left motion without the complication of sinusoidal velocities and alternate sweeping of opposed motions over the same area of the ret-ina. To this end, two diffusion surfaces of milk lucite were mounted physically vertical in the observer's frontal plane equally spaced, one above and the other below the line of sight. A sprocketted drive for 70 mm photographic film was arranged about the diffusion surfaces to pass a continuous loop of film from left to right across the upper surface and return (right to left) across the lower surface or vice versa. A small D.C. generator attached to one of the sprocket shafts provided a voltage proportional to rpm which was displayed on a meter to permit control of stimulus velocity. The velocity used was .24 mm/msec or 17" of arc/msec (24 cm/sec or 4.6°/sec).

The photographic film loop which provided the contour of the moving stimulation was formed of a high contrast negative (Kodalith) printed from a transparent positive on which opaque chart symbols had been mount-ed at random in a checkerboard arrangement to approximately a 30% density. Thus, the moving stimulus which appeared against the background luminance in positive contrast (105.8 mL/6.5 mL or 10.6 mL/.65 mL) was an assort-ment of stars, circles, squares, triangles, and half circles both filled and in outline, ranging in size from 3.4 to 9 min of arc on their longest dimension. The average luminance, without filter, of the stimulus area with the stimulus in motion and continuously exposed was 11.1 mL. The random display was prepared to obviate depth impressions from the fusion of successive elements within the moving stimulus.*

The fixation configuration, formed of low voltage incandescent lamps, was centered in the space between, and in the plane of, the dif-fusion surfaces. It provided a zero referent for depth judgments as well as fixation. Originally it was hoped that the one band of stimulation could serve as referent for the other and eliminate the need for a fixa-tion point, however, pilot work indicated that fixed stimulation was need-ed for stable depth impressions to occur.

The stimulus surfaces, and that of the background illumination were transilluminated by cool white fluorescent tubes under D.C. excitation.

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*Preliminary work with a vertical bar display gave step increments of depth consequent to fusion of successive bars (wallpaper effect). Joint manipulation of stimulus velocity and occluder cyclic rate could also produce apparent movement opposite in direction to the physical movement of the stimulus. Under these conditions, the depth displacements conse-quent to interocular delay or interocular illumination differences, Pulfrich, were consistent with the physical movement, not the apparent movement (10).

The fixation lights were adjusted in intensity by a variable voltage transformer to approximate that of the moving stimulus. All luminance measures were made from the observer's position and were corrected for the sensitivity of the human eye. The angular subtenses of the stimulus display are given in Figure 1.

The rotary occluders composed of 18° segments, alternately opaque and open, were rotated by stepping motors controlled by pulses from a two-channel timer which provided adjustable intervals for the exposure of the individual eye and the sequencing of the exposures of the two eyes. The latter, the interocular delay, was adjusted by a calibrated, multi-turn potentiometer which provided control to ±.2 msec. All fixed time intervals were set with a crystal controlled counter to ±.2 msec. Overall timing within one exposure cycle was ±.4 msec. In addition, there was a cyclic variation over a 10 exposure sequence of ±1.0 msec due to cutting and centering errors in the preparation of the occluders.

Measures and Conditions. Experimentation was conducted sequentially in two parts. Initial concern was with the phenomenon as generated by intermittent exposure of both eyes. Subsequently, "control" data were taken with filters before each eye to assess the Pulfrich phenomenon under comparable conditions and with intermittent exposure to one eye while the other viewed through a filter as a possible intermediate between Mach-Dvořák and Pulfrich. The filters used were calculated in each instance to give Bloch's Law equivalent luminances of the intermittent exposures. Efforts to psychophysically match brightnesses proved inconclusive (11, 12).

The observer's response under all conditions was a subjective estimate of the depth displacement from the fixation lights of the upper and lower bands of moving stimulation. These estimates were made on a personal scale based on the vertical elements of the visual display being 3" in extent. Depth displacements beyond the fixation lights were considered plus and displacements toward the observer minus. Relative depth displacements of one band of stimulation with respect to the other were determined such that displacements, top away - bottom toward, were positive and, top toward - bottom away, negative.

The specific details of the experimental manipulations, measures, and observers are given in Table 1. All combinations of experimental manipulations were used with all observers including judgments with the stimulus standing still. Referent eye designates the eye which received the experimental manipulation. The other eye view was the index exposure (12.5 msec at the higher peak luminance) or was continuous with an 11.3% transmitting filter. When the index exposure was manipulated, it was adjusted in delay only. Delay times were measured from onset of the experimental exposure to onset of the index exposure. The combination of the index exposure with an experimental exposure of equal duration was duplicated for each eye as referent eye. This procedure, although arbitrary, provided for all subsequently derived delay measures to be directly comparable without zero transformation. The equal illumination combinations of the control conditions were not duplicated since they did not involve delay measures. The two levels of luminance of the experimental exposures were obtained by the use of a 1 log neutral density filter before the referent eye. For convenience, stimulus motion was specified in terms of the upper band since both directions of motion were always present in the field of view.

TABLE 1

MANIPULATIONS, MEASURES, AND OBSERVERS

MANIPULATIONS	LEVELS			
1. Exposure Duration (Cyclic interval 110 msec, 9.1 cps)				
Index	12.5 msec			
Filter Equivalent*	11.3 % trans			
Variable	12.5 msec	35.0 msec	55.0 msec	75.0 msec
Filter Equivalent*	11.3 % trans	31.8 % trans	50.0 % trans	68.1 % trans
(1 log down)	1.1 % trans	3.2 % trans	5.0 % trans	6.8 % trans
2. Referent Eye (Variable Exposure)	Left Eye	Right Eye		
3. Stimulus Motion (16.75" of arc/msec)				
Upper Band	Left-to-Right	Right-to-Left		
Lower Band	Right-to-Left	Left-to-Right		
4. Luminance				
Index Exposure				
Stimulus	105.8 mL			
Background	6.5 mL			
Variable Exposure				
Stimulus	105.8 mL	10.6 mL		
Background	6.5 mL	.6 mL		

MEASURES

1. Neutral Points (Delay in msec)	Simultaneous	Alternate

OBSERVERS

Name	Age	Sex	Device	Spectacle Prescription				
S.C.P.	24	F	Contact Lens	OD	-2.50			
				OS	-4.75,	3.00	x	90
H.W.M.	50	F	Spectacles	OD	-4.25			
				OS	-1.50,	.75	x	117
T.E.K.	26	M	None	None				
G.S.H.	52	M	Spectacles	OD	- .50,	.50	x	26
				OS	-1.25,	1.25	x	180

*The percent filter transmittance is also the percent light of the light/dark partitioning of the cyclic interval.

Data. Responses were obtained in 36 sessions per observer, 32 with binocular intermittent exposures and four with filter and uniocular intermittent exposures. The order within each category was dictated by the convenience of the observers and the adjustment of the apparatus. In general, a session was not over 40 min long and no more than one session was accomplished in one day. All sessions were accomplished in approximately 3 months. Two naive observers worked with the situation for only the period of data taking. The author and his assistant worked with the situation for some 18 and 9 months, respectively. Individual response characteristics became apparent early and persisted throughout.

The schema ultimately devised for recording responses with binocularly intermittent exposures involved direct graphing, as illustrated in Figures 2 through 5. Record sheets with a time line representing the delay of the index exposure were prepared with appropriate dial settings shown in the margin. A session was initiated by the experimenter setting a delay of the index exposure and raising the manual shutter. The observer viewed the moving stimulus, fixating and/or glancing up and down until he felt he could make a firm evaluation. (This dependence upon the observer was necessary since the initial impression of depth frequently was not the ultimate impression.) When, in the judgment of the observer, the depth impression was stable, he reported the direction, and subjective magnitude of the depth displacements. The shutter was then closed in preparation for a new presentation and the experimenter recorded the judgments as a pair of points on the time line at the delay which had been set.

This process was repeated with free selection of delay times directed first toward locating and defining the neutral zones and, second, toward filling in intermediate points. Intermediate judgments were generally easier and were used to provide a respite from the more difficult, neutral zone judgments (13). View of the moving stimulus was occluded between presentations to obviate time-order effects which were evident in pilot work. No information as to the adequacy of judgments was given except on the occasion of an unduly long session; occasioned by a persistent confusion, the observer might be informed that he was being asked to repeat a judgment.

Since interocular delay was meaningless with monocular intermittence and filter exposures, the response to these combinations was a single set of magnitude estimates. To provide stability in these measures, the combinations were repeated three times at random and a mean difference taken. Three identical judgments were not unusual though differences as great as five units also occurred.

Observers. Four observers were used. Their visual characteristics, age, and sex are given in Table 1. The prescription indicated in the table was worn by the individual when serving as an observer.

RESULTS

Certain of the results of the investigation are immediately evident from the data as initially recorded. Figures 2 through 5 are each a composite of the data for four of the 32 experimental sessions for one observer. As a group, these figures sample half of the experimental combinations under which data were taken. The balance of the data repeats these combinations with a 1 log filter before the referent eye and is similar to those shown though this manipulation did at least four things: 1) it reduced the luminance of the binocular view, 2) and 3) it reduced the peak, and average luminance of the experimental exposure, and 4) it reversed the order of the interocular illumination differences which with the Pulfrich phenomenon results in a reversal of the perceived depth relations.

Coding and Individual Differences. The sign of the perceived relative depth is given in Figures 2 through 5 by the position of the filled circles and the open diamonds. When the open diamonds appear above the solid circles, the difference is positive, i.e., the upper band of stimulation was perceived as farther from the observer than the lower band. The converse is negative. The effective eye sequencing is given by the relative position of the dotted and solid lines. When the dotted line is above the solid line, sequencing is right eye before left eye and vice versa. A further detail of the responses is evident in the clusters of unconnected symbols usually associated with an alternate neutral point. These represent multiple judgments made when the depth impression continued to change throughout the period of observation. Frequently the fluctuation involved only one band of stimulation though all possible combinations were seen on different occasions.

Observer to observer consistency is evidenced in that the four figures are representative of the findings of the study though they are one from each observer. Distinct individual differences are evident. For instance, observer G.S.H. seldom reported negative relative depth and when he did the depth difference usually was small and accompanied by displacement of both the upper and lower bands of stimulation toward the observer. Displacement of neutral points forward or behind the fixation lights also seemed to be observer related (forward for G.S.H. and S.C.P., behind for H.W.M.).

Neutral Zones. These four figures each illustrate the change in time of occurrence of the neutral zones (points of coincidence or crossing of the solid and dotted lines) with increase in exposure duration. Exposure durations are represented on the time axis by the space between the onset (⌈) and offset (⌉) marks. (Marks are above or below the time line to indicate the eye so stimulated, the referent eye. The opposite eye received the index exposure.) Clearly, the delay of both the alternate and the simultaneous neutral zones increases, though at a different rate, with

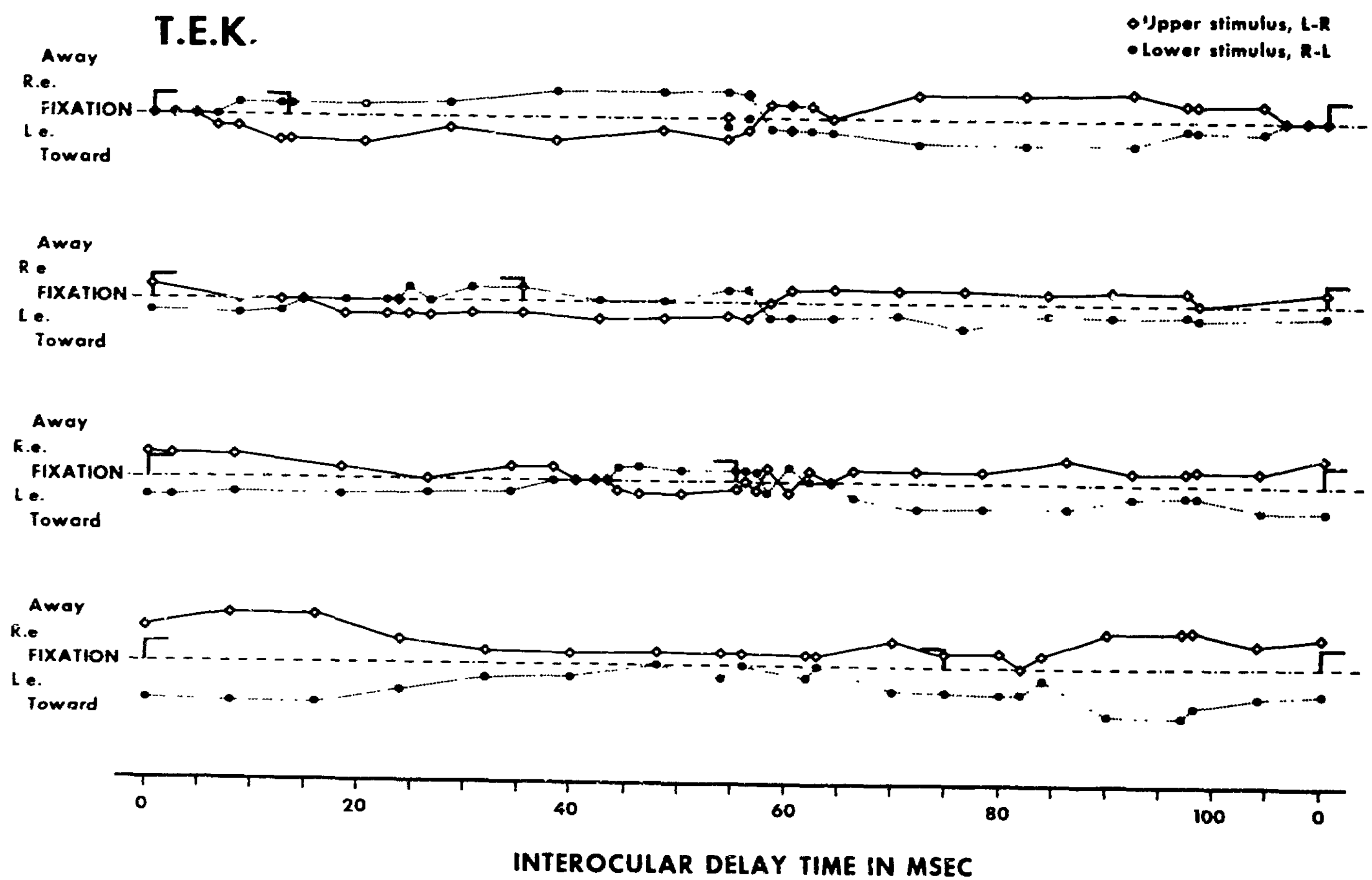

Fig. 2. Responses as originally recorded showing the change in time of occurrence of neutral points with duration of the variable exposure to the right eye for left-to-right motion of the upper stimulus band. (Observer T.E.K.) The onset (┏) of the variable exposures to the referent eye is at the left at time zero, the offsets (┓) were as indicated. Direction of judged depth displacement, away or toward the observer, is coded above and below the fixation line.

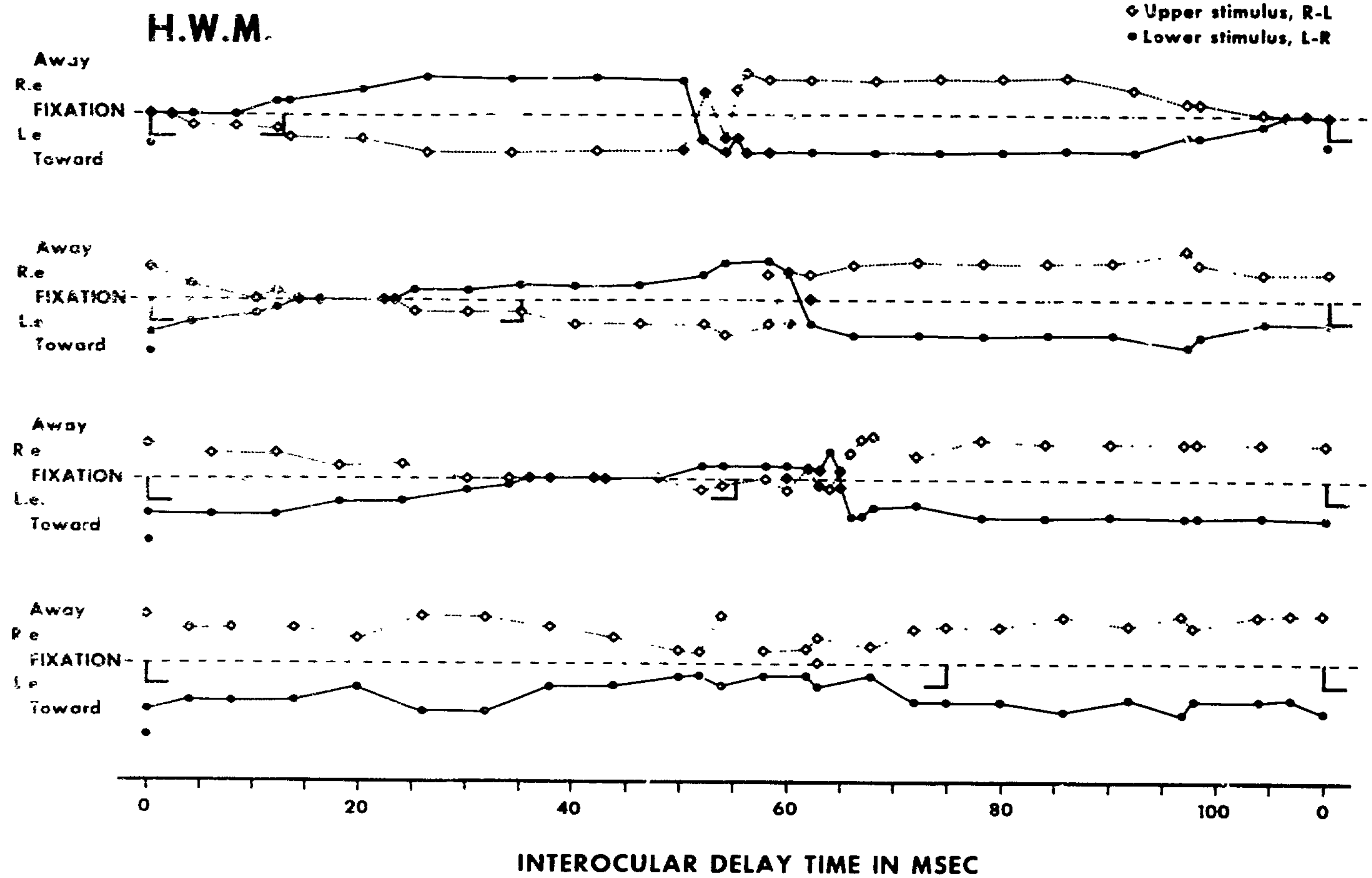

Fig. 3. Responses as originally recorded showing the change in time of occurrence of neutral points with duration of the variable exposure to the left eye for right-to-left motion of the upper stimulus band. (Observer H.W.M.) The onset (┏) of the variable exposure to the referent eye is at the left at time zero, the offsets (┓) were as indicated. Direction of judged depth displacement, away or toward the observer, is coded above and below the fixation line.

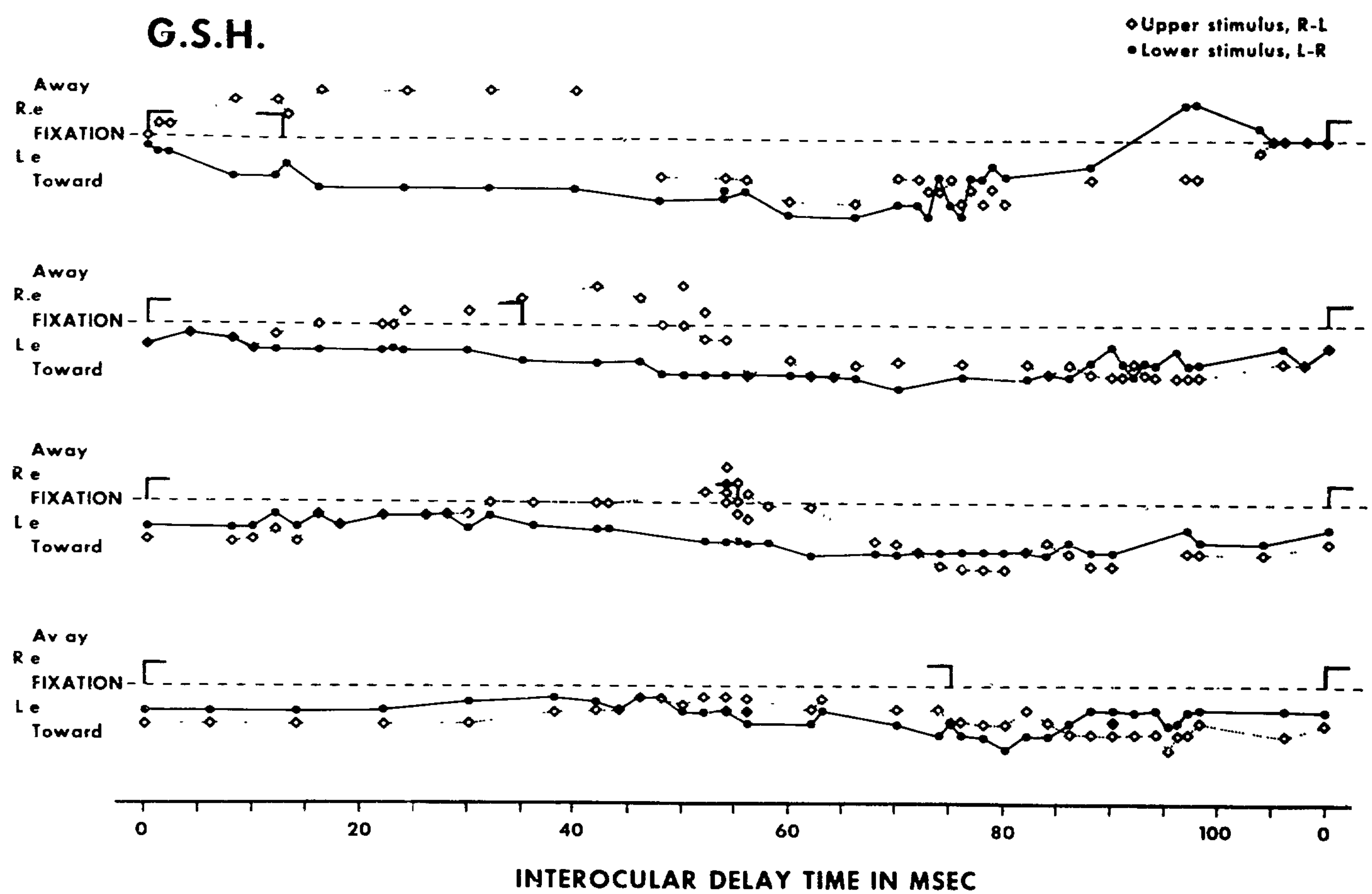

Fig. 4. Responses as originally recorded showing the change in time of occurrence of neutral points with duration of the variable exposure to the right eye for right-to-left motion of the upper stimulus band. (Observer G.S.H.) The onset (┌) of the variable exposure to the referent eye is at the left at time zero, the offsets (┐) were as indicated. Direction of judged depth displacement, away or toward the observer, is coded above and below the fixation line.

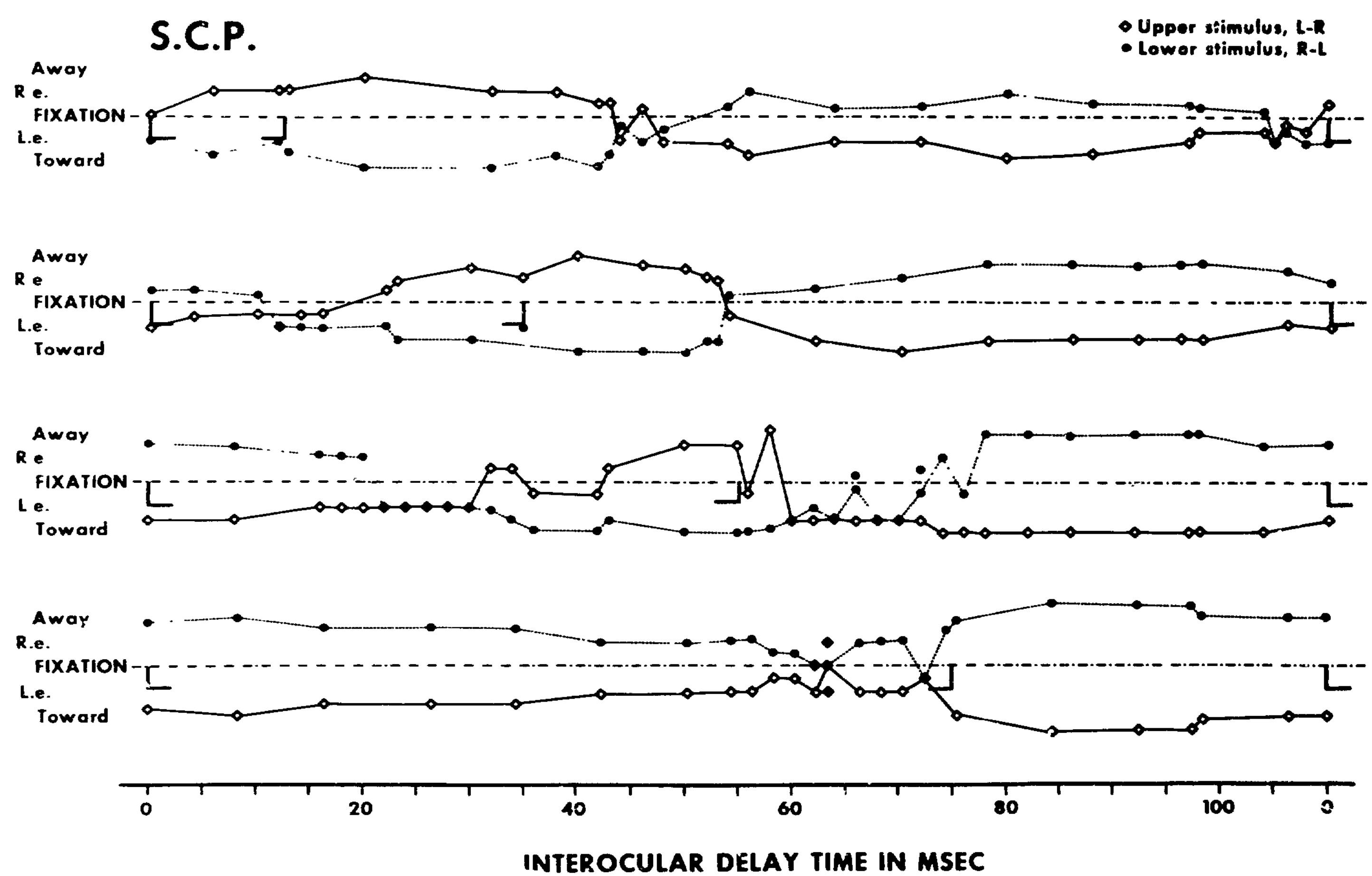

Fig. 5. Responses as originally recorded showing the change in time of occurrence of neutral points with duration of the variable exposure to the left eye for left-to-right motion of the upper stimulus band. (Observer S.C.P.) The onset (⌈‾) of the variable exposures to the referent eye is at the left at time zero, the offsets (‾⌉) were as indicated. Direction of judged depth displacement, away or toward the observer, is coded above and below the fixation line.

increased duration of the experimental exposure. Interestingly, the neutral zones disappear in Figures 2 and 3 for the 75 msec exposure. The perceived relative depth displacement which persists, top away and bottom toward or vice versa, is consistent with the eye which received the short--the index exposure always preceding the eye which received the long exposure. It is as though the short exposure precedes the long exposure in time of perception. Thus, with increased exposure duration, there has been a transition from eye sequence to exposure duration as the feature which determines the perceived relative depth displacement.

Figures 2 and 3 (left-to-right movement of the upper band in combination with right referent eye and vice versa) and Figures 4 and 5 (right-to-left movement with right referent eye and vice versa) seem to be duplicate determinations though the experimental combinations are different. Characteristically, the relative depth preceding the simultaneous neutral zone is positive for Figures 2 and 3 and negative for Figures 4 and 5. This difference in the effect of direction of motion as a function of referent eye was subsequently confirmed in the quantitative measures of neutral point delay.

Quantitative Measures. Quantitative measures were derived from the data by determining the midpoint of the zones of "no perceived depth difference." The delay from the onset of the experimental exposure to the last and first clearly seen depth difference preceding and following each neutral zone was averaged and this midpoint recorded as the delay of that neutral point. A set of rules that could be applied with consistency was developed to resolve indeterminacies. With G.S.H., who seemed consistently to provide three neutral zones, the last neutral point preceding the onset of the experimental exposure was taken as the alternate neutral point. A table of 256 delay times was thus obtained, one measure for each observer for each combination of exposure duration, luminance level, stimulus direction, referent eye, and neutral point (see appendix Tables 1 and 2). The value 48.8 msec was used as dummy data on seven occasions when no meaningful value could be established in the absence of a neutral zone. (This value effectively placed the midpoint of the index exposure at 55 msec, the midpoint of the cyclic interval.) The data of G.S.H. and T.E.K. for the two levels of luminance, in conjunction with the 75 msec exposure duration in the combinations illustrated in Figures 2 and 3, accounted for all seven occasions. The extent of the neutral zones and the magnitude of the perceived depth difference immediately adjacent in time were also determined. Only the midpoints showed systematic changes with the experimental manipulations.

Statistical analysis. The obtained data were subjected to a five way analysis of variance for repeated measures (referent eye, exposure duration, luminance level, direction of movement, and neutral point) with four measures per cell (one per observer). The resultant analysis was dominated by the interaction of direction of stimulus movement and referent eye evident in the pairing of Figures 2 - 3, and 4 - 5. In keeping with this finding, the data were further summarized by averaging the delay times for 'right referent eye in combination with left-to-right motion,' with those for 'left referent eye in combination with right-to-left motion.' This new category of measures was designated "divergent," and is characterized by positive relative depth preceding the simultaneous neutral point. The scores for 'right referent eye with right-to-left motion' were averaged with 'left referent eye and left-to-right motion' and designated "convergent." This category is characterized by negative relative depth preceding the simultaneous neutral point.

A four way analysis of variance for repeated measures of the data in this form (128 delay times) gave statistically significant F ratios for the following factors: the simple factors of neutral point and exposure duration (1/3, 1/9 df, $p < .001$), and illumination (1/3 df, $p < .025$); two factor interactions of neutral point with luminance level, and exposure duration (1/3, 1/9 df, $p < .001$), and the new vergence factor (1/3 df, $p < .05$); and a three factor interaction of neutral point with luminance level and exposure duration (1/9 df, $p < .005$). The significance of neutral point as a simple factor is trite since they were defined to be different in the scoring of the response sequences; however, the interactions of this variable are real experimental outcomes and are indicative of the complex relation of the intermittent exposure phenomena to the possible experimental manipulations.

Exposure duration. The means of this second analysis of variance are graphed in Figures 6 and 7 and given in numerical form in Tables 2 and 3. The data of Figure 6 are for the divergent measures and those of Figure 7 are for the convergent measures. The variable, exposure duration, is illustrated below the time line in two vertical extents to differentiate the two peak luminances. The index exposure is represented above the time line and is positioned in delay as the simultaneous (solid) and alternate (dotted) neutral points occurred.

The neutral points of Figure 6 generally lag the neutral points of Figure 7. The neutral points for the exposure combination of 75 msec at high luminance in Figure 6 are shown as a single alternate neutral point (A) since the perceived depth reported was positive and characteristic of the interval between an alternate and the next succeeding simultaneous neutral point. No observer evidenced more than one neutral point for this combination. The mean value represented is due primarily to the arbitrarily assigned delay of 48.8 msec. The simultaneous neutral points of Figure 6 tend to be delayed within themselves more than to those of Figure 7. The reverse is true of the alternate neutral points. Clearly, the alternate neutral point is not a simple, cyclic return to the precondition for the next simultaneous neutral point. However, a nearly identical delay pattern for the simultaneous and alternate neutral points was obtained for the reduced luminance combinations presented in the lower portion of Figure 7.

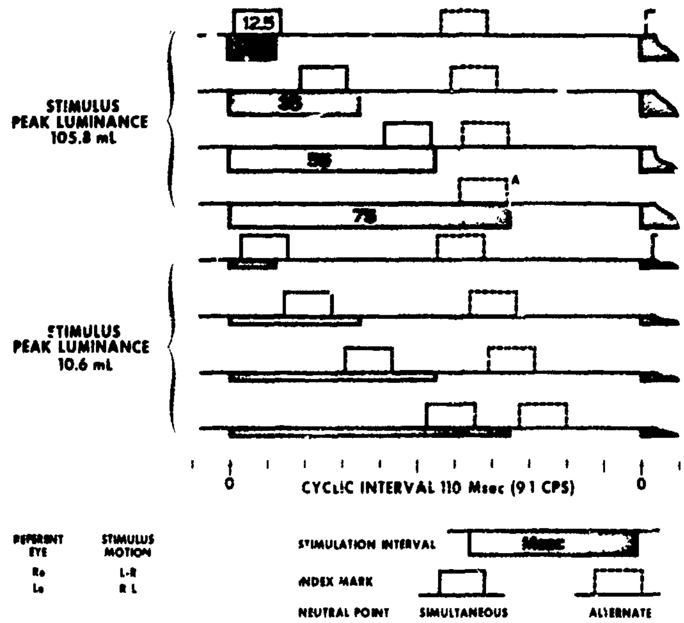

Fig. 6. Pictorial summary of the change in time of occurrence of the simultaneous and alternate neutral points for the divergent data category as a function of peak luminance and light/dark partition.

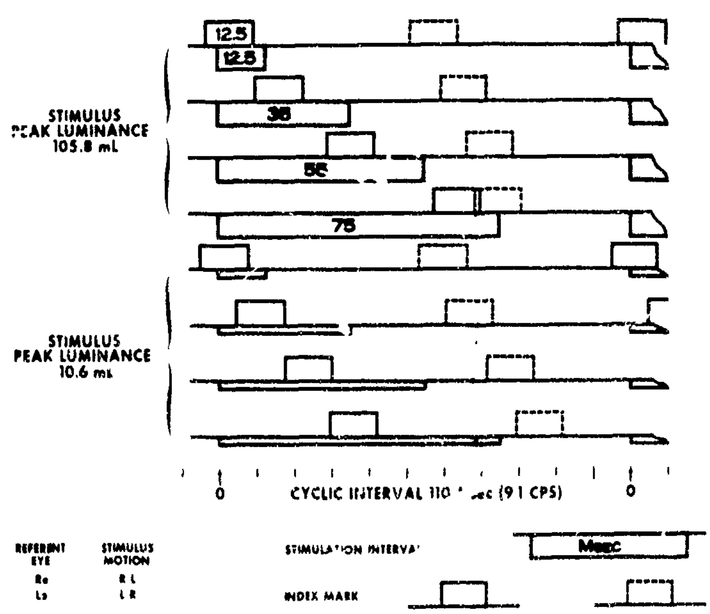

Fig. 7. Pictorial summary of the change in time of occurrence of the simultaneous and alternate neutral points for the convergent data category as a function of peak luminance and light/dark partition.

TABLE 2

DELAY OF THE SIMULTANEOUS NEUTRAL POINT IN MSEC AVERAGED ACROSS OBSERVERS (N = 4)

	Exposure Duration in Msec			
	12.5	35.0	55.0	75.0
Divergent*				
High Luminance				
Mean	1.6	19.2	41.3	61.7
Standard Deviation	1.8	2.3	3.0	3.7
Low Luminance				
Mean	3.1	14.7	31.0	52.7
Standard Deviation	4.4	3.1	5.0	4.2
Convergent**				
High Luminance				
Mean	-3.0	11.1	29.1	57.2
Standard Deviation	1.9	4.4	5.3	7.9
Low Luminance				
Mean	-4.8	4.8	17.5	29.6
Standard Deviation	4.0	4.1	5.6	11.4

*Post hoc data category which combines the experimental conditions of right referent eye and left-right motion with left referent eye and right-left motion.

**Post hoc data category which combines the experimental conditions of right referent eye and right-left motion with left referent eye and left-right motion.

TABLE 3

DELAY OF THE ALTERNATE NEUTRAL POINT IN MSEC AVERAGED ACROSS OBSERVERS (N = 4)

	Exposure Duration in Msec			
	12.5	35.0	55.0	75.0
Divergent*				
High Luminance				
Mean	56.6	59.2	62.3	61.7
Standard Deviation	2.7	8.9	5.0	3.7
Low Luminance				
Mean	55.5	64.4	69.2	77.5
Standard Deviation	7.5	6.4	6.7	4.7
Convergent**				
High Luminance				
Mean	51.5	59.1	66.2	68.4
Standard Deviation	5.2	8.7	3.7	4.5
Low Luminance				
Mean	53.6	60.5	71.6	79.3
Standard Deviation	4.7	6.9	6.5	7.1

*Post hoc data category which combines the experimental conditions of right referent eye and left-right motion with left referent eye and right-left motion.

**Post hoc data category which combines the experimental conditions of right referent eye and right-left motion with left referent eye and left-right motion.

Retinal illumination. The interrelations of the neutral point delay times for the high and low peak luminances are generally the converse of those for the divergent-convergent measures. The simultaneous neutral points become less distributed in delay with reduced luminance and the alternate neutral points become more distributed. Significantly, there is no general delay of all neutral points with reduced luminance and, as noted earlier, the relative depths perceived are not reversed by a reversal of the interocular illumination differences. All but one of the simultaneous neutral points are reduced in delay; all but two of the alternate neutral points are increased in delay. Considered in the context of increased conduction latency with reduced retinal illumination, the effects observed are contradictory for the simultaneous neutral points and confirmatory for the alternate neutral points.

In Figure 8 the same means are graphed on conventional axes. The plots for the alternate neutral points are shifted up for clarity.

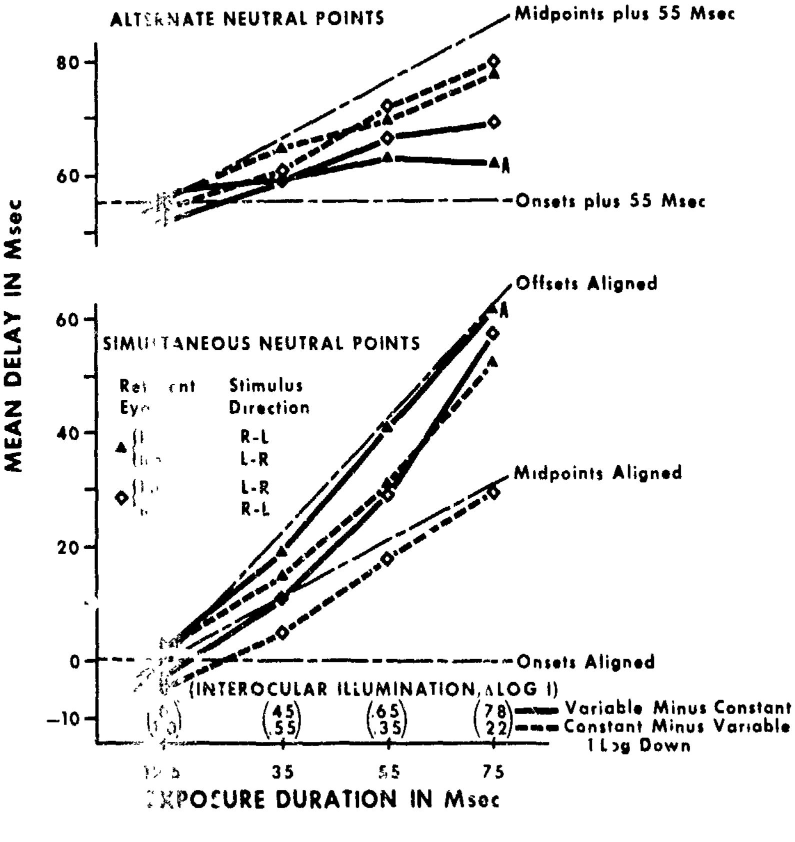

Fig. 8. Rectangular coordinate summary of simultaneous and alternate neutral point measures. Plot of alternate neutral points is displaced upwards for clarity. Point A is common to both portions of the figure. Solid triangles present the divergent data category, the open diamonds present the convergent data category.

Point A in the upper and lower portions of the figure is the point A of Figure 6. The principal abscissa is the duration of the experimental exposure. The two additional abscissa values give the concomitant interocular illumination differences, Δ log I. There is also a general binocular luminance increase from left to right in the figure consistent with the increase in duration of the experimental exposure. Thus, the dashed versus the solid lines in the figure represent the effect of reduced peak and average luminance and a reduction through zero of the interterocular illumination differences. The opposed response of the alternate and simultaneous neutral points to the change in stimulus luminance is evident in the position of the dashed and solid lines relative to one another in the upper and lower portions of the figure.

Fusion referent. Dashed lines have been provided within Figure 8 to represent the change of delay with increased duration of the experimental exposure for the possible simple outcomes of onset, midpoint, or offset as the fusion referent for eye sequencing. Delay of the onset of the index exposure in fixed relation to the onset of the experimental exposure would appear as a horizontal line in the figure. This outcome is represented for the simultaneous and alternate neutral points by the lines designated "onsets aligned" and "onsets aligned plus 55 msec." Similarly, the other dashed lines represent coincidence of the midpoints of both exposures and of the offsets of the exposures. The multiple interaction of neutral point with the post hoc vergence factor and illumination level is evident in the change in relative slope of the data lines for the various conditions. There is almost a progression of the simultaneous neutral points from offsets aligned to midpoints aligned with a counter progression of the alternate neutral points from onsets aligned to midpoints aligned.

There is a suggestion that the neutral points of the equal exposure combinations are unique, or at least represent a different order of relationship. The effect of luminance for these points is reversed from the other exposure durations. The consistency across observers of the direction of these differences with change of luminance is given in Table 4. Table 5 gives the differences per se and their statistical significance when tested against the highest order interaction with observers of the analysis of variance.

"Controls." The data for the four observers obtained with monocular, intermittent exposures and Bloch's Law equivalent luminances are presented in Figure 9. Each point is the mean of six judgments (see appendix Table 3). One for one substitution of filter for exposure duration in the taking of these judgments maintained the interocular illumination differences generated by the intermittent exposures. Values of Δ log I have been plotted from negative on the left through zero, or equal, to positive on the right to depict the reversal of direction of the generated interocular differences. There is also the binocular luminance increase from left to right noted previously consequent to the use of the 1 log filter to obtain the negative interocular illumination differences and the increasing exposure durations shown as a concomitant abscissa.

TABLE 4

CONSISTENCY ACROSS OBSERVERS OF DIRECTION OF DIFFERENCES IN DELAY FOR LOW MINUS HIGH LUMINANCE

	Variable Exposure Duration in Msec			
	12.5	35.0	55.0	75.0
Simultaneous Neutral Point				
Divergent	3/4*	(-) 4/4	(-) 4/4	(-) 2/2**
Convergent	(-) 3/4	(-) 4/4	(-) 4/4	(-) 4/4
Alternate Neutral Point				
Divergent	(-) 2/4	4/4	4/4	2/2**
Convergent	4/4	2/4	4/4	4/4

*Read "Delay of the simultaneous neutral point was greater with the low luminance, and the divergent combinations of stimulus motion and referent eye for three of the four observers."

**No neutral points for two observers.

TABLE 5

DIFFERENCES IN MILLISECONDS OF DELAY FOR LOW MINUS HIGH LUMINANCE

	Variable Exposure Duration in Msec			
	12.5	35.0	55.0	75.0
Simultaneous Neutral Point				
Divergent	1.5	-4.5	-10.3	- 9.0*
Convergent	-1.8	-6.3	-11.6	-27.6
Alternate Neutral Point				
Divergent	-1.1	5.2	6.9	15.8*
Convergent	2.1	1.4	5.4	10.9

Critical Differences: 3.67, $p < .05$; 5.27, $p < .01$; df 1/120

*Dummy data used for two observers.

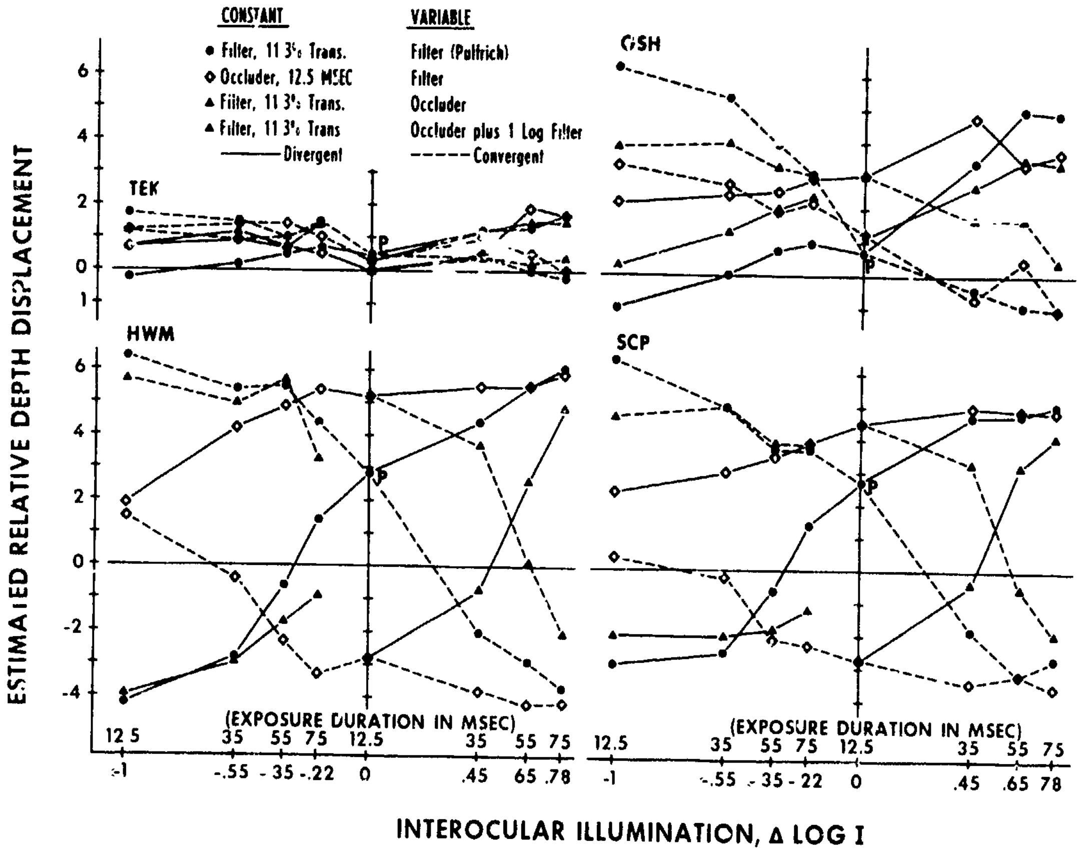

Fig. 9. Perceived relative depth displacement (upper minus lower band) for the individual observers with filter before both eyes (Pulfrich) and intermittent exposure of one eye only as a function of interocular illumination difference.

The use of filters to provide equivalent luminances substituted an infinite exposure for what had been a determinate exposure and the referent eye exposure was no longer, necessarily, the longer exposure. However, in keeping with the one for one substitution of equivalent luminances, the data combinations established with binocular intermittence were maintained in the analysis. For the Pulfrich data, with no intermittency, i.e., interocular illumination differences only, this procedure resulted in a partitioning of the relative depth data as increasing either positively or negatively with increasing interocular illumination difference. For the 12.5 msec index exposure in combination with filters substituted for the experimental exposures, the combinations remained functionally consistent since the index exposure was the shorter. With the substitution of the 11.3% transmittance filter for the index exposure, the functional combinations were reversed and the generalization of variables confounded by the change in duration of the shorter, the experimental exposure, and the presence of two peak luminance levels in the experimental exposure consequent to the use of the 1 log filter to reverse the direction of the interocular illumination differences.

Statistical analysis. A four way analysis of variance of the data (vergence combination, direction of illumination difference, viewing conditions, and exposure duration, with repeated measures on the four observers) produced the following statistically significant F ratios: the simple factors of, exposure duration (3/9 df, $p < .005$), and direction of illumination difference (1/3 df, $p < .05$); the two factor interactions of viewing conditions with duration (6/18 df, $p < .01$), direction of illumination difference (2/6 df, $p < .025$), and direction of illumination difference with exposure duration (3/9 df, $p < .025$); and the three factor interaction of direction of illumination difference, viewing conditions and exposure duration (6/18 df, $p < .05$). The vergence factor was not statistically significant ($p < .20$). This lack of significance is attributed to the confounding noted above. The trite interaction of the vergence factor and exposure duration (the dotted versus the solid lines in the graphs) was eliminated prior to analysis by the device of rotating the data for each observer about point P as a point of symmetry.

Pulfrich. The data plotted with filled circles show an essentially linear relation between perceived relative depth and Δ log I over the range of luminance of the study. Distinct individual differences are evident in the magnitude of the depth perceived and its relation to Δ log I. Least squares fits of the data give slope values from .98 to 6.47 with all y intercepts positive, ranging from .77 to 2.00 (see Table 6). The fact that the fitted lines do not pass through the point 0,0 suggests that Pulfrich is subject to an observer bias for movement. This is supported by the fact that no observer reported depth displacement when the stimulus was not in motion.

Constant exposure. Comparison of the data shown in open diamond in the figure with that obtained with filter only (Pulfrich) traces the relative effect of viewing the moving stimulus with the index exposure in combination with increasing luminance to the other eye. The change in perceived relative depth from that obtained with Pulfrich is consistent with "the short exposure precedes the long exposure in time of perception." (All slope values [m] in Table 6 are smaller for the 12.5 msec exposure data than for the Pulfrich data.) Simple additivity of the disparities produced by intermittence and conduction latency would predict a series of data points displaced but parallel, i.e., of equal slope. Rather, there seems to be a progression from displacement at the left to communality at the right. Apparently, the specification of an exposure interval to one eye delineates a unique relation of the perceived relative depth displacement to the variable of interocular illumination difference or its concomitant, binocular luminance. The identity of data points at the right of the figure may represent the maximum relative depth available in the experimental situation.

TABLE 6

PARAMETERS OF LEAST-SQUARES, LINEAR PREDICTION ($y = mx + b$) OF ESTIMATED RELATIVE DEPTH DISPLACEMENT FROM Δ LOG I BY INDIVIDUAL OBSERVERS FOR THE DATA OF FIGURE 9

Observer	Pulfrich						12.5 Msec Constant Exposure					
	Divergent			Convergent			Divergent			Convergent		
	m	b	r	m	b	r	m	b	r	m	b	r
TEK	.98	.77	.97	-1.11	.77	-.94	.53	.88	.52	- .63	.83	-.75
HWM	6.02	1.76	.98	-6.47	1.81	-.96	1.74	4.86	.84	-2.98	-2.53	-.92
GSH	3.55	1.94	.96	-4.58	2.00	-.97	1.10	3.15	.80	-2.40	1.18	-.95
SCP	5.07	1.73	.96	-5.87	1.55	-.98	1.51	4.06	.96	-2.19	-2.18	-.92

Variable exposure. The data presented in open and filled triangles are properly compared with one another (left hand portion of the figure with the right hand portion) as representative of equivalent, progressively longer, monocular intermittent exposures at two levels of peak luminance. Since opposite eyes received the experimental and constant exposures to generate the binocular intermittent conditions, the process of one for one substitution provided that the monocular intermittent conditions of the divergent-convergent combination of the data would be identical for $\Delta \log I = 0$ and $\Delta \log I = -1$ though with the expectation of perceived relative depths of opposite sign. The relation between these pairs of points as pairs is that of a 1 log difference in peak luminance of the intermittent exposure. The fact that these values are symmetrical about a positive value rather than 0,0 again suggests the presence of observer bias.

Simple summation of disparities is again denied in that the $\Delta \log I = -1$ data points do not evidence greater relative depth displacement than the associated Pulfrich values. Since this condition combines the -1 log, interocular illumination difference with the intermittence of the equal or zero, interocular illumination difference condition, both of which singly produced negative relative depths, summation would predict even greater negative relative depth. The latter did not occur. From left to right in the figure, the variable exposure interacts with luminance. Each set of determinations approaches its associated filter-only equivalent. It would appear that the greater exposure durations lose the characteristic of intermittence and become effectively a filter (see Figures 2 and 3).

DISCUSSION

A comparison of the techniques of this study with those of other recent studies (6,7) reveals certain identities and differences which evidence the robustness of the phenomenon. Harker, initially and in the current work, used a physical, binocularly viewed object as the moving stimulus. Lee used a stereoscopically generated object. Both Harker and Lee generated the phenomenon, as did Dvořák, by controlled intermittence of all stimulation--both fixed and moving. Harker used both low and high speed episcotisters while Lee used electronically controlled light flashes. Both sinusoidal and linear movement of the stimulus has been used. Sinusoidal, maximum velocities of 23.4° and 29.0°/sec or, respectively, average velocities of 8.0° and 19.9°/sec were used by Lee and Harker. The present work was accomplished with a uniform velocity of 4.6°/sec.

Positive contrast was used by Harker, generated by a white object against a black background, in the earlier instance, and, in the present instance, by a bright-line, transilluminated stimulus against a superimposed background luminance. Lee used the negative contrast of a stereoscopic shadow against the background illumination which produced the shadow. Both researchers worked at some aggregate adaptation level consequent to the light/dark intervals used, the positive or negative contrast of the stimulus, and the sum of the luminosity X area relations present in the overall field of view. Subsequent research by the author has used flashed, stereoscopic, transilluminated stimuli, superimposed upon a steady background luminance in a situation, in its pertinent aspects, much like that used by Dodwell et al (14) to study the Pulfrich phenomenon.

The Mach-Dvořák phenomenon conceptualized geometrically results from the movement of the stimulus during the delay of stimulation to the separate eyes. The movement generates a relative disparity between the moving stimulus and fixed stimuli in the field of view common to the two eyes. With zero delay and equal exposure durations, no differential movement can occur and the depth perceived should be veridical, i.e., the simultaneous neutral point should coincide with zero delay. The introduction of a luminance difference should induce a depth displacement consistent with delay of the filtered eye provided the exposure durations are sufficiently long that the stimulus provided can constitute the continuous stimulation characteristic of Pulfrich (8). The fact that the data for the 12.5 msec exposure condition of the present study do not conform to expectation would seem to need explanation (see Tables 2 and 3, and Figures 6 and 7). Conceivably, there was some situational bias, yet the simultaneous neutral points both lead and lag the requisite zero delay, depending upon the post hoc data category, and no observer reported perceived depth displacement when the stimulus was viewed, at rest, with no intermittence and no luminance difference. In general, these differences were too small to be statistically significant, but the consistency across observers is suggestive.

There were 32 equal exposure determinations in the data, eight per observer for four combinations of conditions. For the equal luminance conditions--with the divergent data, seven of the eight determinations (two per observer) were positive, and with the convergence data, all eight were negative. For the 1 log imbalance of luminances--with the divergent data, six of the eight determinations were positive, and with the convergent data, seven of the eight were negative. Similarly, there were 24 judgments taken with equal luminance and infinite exposures--of which, 18 were positive. The resultant mean differences were positive for all four observers, the points P in Figure 9.

The plus and minus partitioning by post hoc category of the simultaneous neutral points for the 12.5 msec exposure conditions suggests the possibility that the depth displacements seen with zero delay are the result of an additive interaction of some feature of the stimulation with an observer characteristic. The known nasal-temporal, retino-cortical conduction time difference of 3-5 msec (15) is of the right magnitude to provide an explanation with the post hoc assumption that: stimulation directed toward the fovea from the lower visual field is preeminent in the resultant cortical integration. (Research supports this particular combination though the converse would do as well since all combinations of stimulus conditions were used (16,17). Given this assumption, the positive relative depth with equal luminance to both eyes and infinite exposure is directly derived as is the observed symmetry of the "control" data about point P. The positive and negative displacement of the simultaneous neutral point with equal exposure durations (Figures 6 and 7) is explained as an additive interaction of the depth induced by the nasal-temporal delay with the characteristic, opposed depth displacements of the post hoc categories. The increased interaction consequent to the reduction of peak luminance follows from the decreased illumination of the referent eye and the consequent increased delay of its temporal retina.

Similar positive zero bias was found by Dodwell et al (14) with intensive measures on four observers, none of whom is represented in the present sample. In this work a sensitivity to the direction of stimulus motion was also evident in the slope parameter relating interocular Δ log I to visual latency. The present formulation does not account for this but would classify the data for those experimental conditions which produced increased vergence as convergent and those which produced decreased vergence as divergent. With the reservation that displacement of a moving stimulus from a fixed referent may not be the equivalent of relative displacement between two moving stimuli, the current formulation would predict discontinuity of function about the equal luminance condition. This is supported grossly by the data obtained for two of the four observers.

The present findings are not to be confused with those of Lee (8) in that the D interval (Lee's terminology) of 110 msec exceeds the limit he found for the demonstration of retinal, lateral inhibition.

Within the geometric formulation of the Mach-Dvořák phenomenon, the simultaneous neutral point marks the occurrence of zero disparity, the fusion referent, and the alternate neutral point marks the occurrence of maximum disparity between the fusion referent in succeeding cycles of stimulation. With the 12.5 msec exposure to the two eyes, the simultaneous and alternate neutral points approximate the timing relations appropriate to a single point of zero disparity per cycle of stimulation. These data essentially duplicate Lee's (6) demonstration that the time from offset to onset of the successive stimulation is the interval which determines the sequencing of the two eyes. The relation is complicated, however, in that with increased exposure duration there is a suggestion of multiple referent points and of a discontinuity between the short, equal exposure conditions and the longer, unequal exposure conditions.

The almost one for one delay of the simultaneous neutral point with increasing duration of exposure (divergent, high luminance, Figures 6 and 8) suggests that it marks some aspect of the off-response. The lack of delay of the corresponding alternate neutral point suggests that it falls between the off-response marked by the simultaneous neutral point and a following on-response (18,19). The occurrence of only an alternate neutral point for the divergent category with the 75 msec exposure and high luminance seems to be the result of the inhibition of the off-response by the next succeeding on-response in the cyclic stimulation. The loss of the off-response apparently terminates intermittence as well (20). The relative depth perceived is consistent in direction with the interocular illumination difference, and corresponds to that obtained with the 12.5 msec, index exposure "control" condition (Figure 9). The preeminence of the short exposure in setting up the associative relation between the two eyes is evident in the absence of an eye sequence change (positive and negative relative depth). The sensitivity to delay evident in the data of Figures 2 and 3 is possibly the consequence of perceptual processes such as "equidistance" (21) and "Panum's limiting case" (22,23).

The situation is further complicated with reduced luminance. Contrast of the intermittent stimulation in the individual eye with the summated binocular background as discussed by Treisman (24) may be the significant variable. The failure of reversal of perceived depth with reversal of direction of interocular $\Delta \log I$ is suggestive. Wicke et al (25) have shown that duration can substitute for luminance consistent with Bloch's Law to maintain a constant pattern in the evoked cortical potential. Engel (26) has demonstrated that stimulus energy defined as the product, intensity X duration, is a critical variable in the stereoscopic response to brief stimuli. The inference would follow then, that reduced luminance with constant duration should result in reduced latency, the opposite of the expectation for an on-response and the latency explanation of the Pulfrich phenomenon. This complexity would be resolved if binocular coordination were initiated by the on-response, with its characteristic increased latency with decreased luminance, while stereopsis, the informational aspects of the stimulation, was carried by later elements of the cortical potential with latency characteristics appropriate to the off-response. This allocation of function is consistent with the suggestion by Julesz (27) that the time constant for stereopsis might exceed that of the cyclopean view. It is also consistent with the suggestion of Engel (26) that the initial stage of stereoscopic vision is retinal, and the second stage central at a point in the nervous system where binocular combination takes place. How the above would interact with the nasal-temporal partitioning to produce the seeming smooth transition of the "fusion referent" from offset to midpoint (convergent, low luminance, Figures 7 and 8) is not apparent.

Subsequent research utilizing a stereoscopic wander-mark to assess the perceived depth (28) has confirmed the finding of the depth estimation data that the alternate neutral point is not necessarily as abrupt as might be expected from Lee's (6) percent judgment data. With a stimulus velocity of 17"/msec and a cyclic interval of 120 msec, a half-disparity interval of 60 msec or less (an interval within the critical duration for stereopsis (22,29,30)), the magnitude of the depth perceived increased to a maximum and declined before the alternate neutral point was achieved. A converse increase to maximum with subsequent decrease to the simultaneous neutral point occurred as the delay of the index exposure was further increased. Geometrically, the relation of perceived depth to interocular exposure delay should be specifiable about the simultaneous neutral point in terms of the parameters of the experimental situation. The determinants of the gradual change in the perceived relative depth about the alternate neutral point are not immediately apparent. The change may be due to the perceptual processes mentioned above, the choice of experimental parameters (stimulus velocity, etc.), or it may be evidence of the interplay of functional processes.

CONCLUSIONS

1. Manipulation of the relative, interocular exposure duration demonstrated a progression from eye sequence, with equal exposures, to "the short exposure precedes the long exposure," with unequal exposures, as the determiner of the relative depth perceived. Conceivably, the neural characteristics operative in determining the effective eye sequence of short and long exposures are also effective in eye sequencing when the exposures are equal.

2. The simultaneous and alternate neutral points, though their occurrence is concomitant to the cyclic nature of the stimulation, were not conjugate in their response to the experimental manipulations. Both neutral points were responsive to exposure duration, albeit to a different degree, and in a manner suggestive of the operation of multiple fusional processes.

3. Manipulation of the luminance level viewed by the referent eye, to reverse the direction of the concomitant interocular illumination difference, produced changes both consistent and inconsistent with the conduction latency explanation offered for the Pulfrich phenomenon. The

physical upper limit of perceived depth with manipulation of exposure duration was consistent with that obtained with Δ log I differences alone and evidenced no discontinuity as the limit of intermittence was approached.

4. Evidence for a time-locked fusion referent was not obtained. Rather, the data indicated a complex interrelation of several possible experimental manipulations in determining the time of occurrence of the fusion referent.

5. Nasal-temporal conduction time differences seem to be clearly evident in a post hoc divergent-convergent categorization of the obtained data.

6. Simple additivity of the disparities from interocular illumination difference and intermittence was not demonstrated. Rather, the manipulation of intermittence and luminance produced interactive effects. Thus, the latency explanation of Pulfrich is not directly generalizable to Mach-Dvořák, however, no barrier is offered by the obtained data to the generalization of an explanation of the Mach-Dvořák to the Pulfrich phenomenon.

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A P P E N D I X

TABLE 1

DELAY IN MSEC OF SIMULTANEOUS NEUTRAL POINT

Observer	Vergence Category		Referent Exposure Duration in Msec			
Luminance	Referent Eye	Movement (Upper Belt)	12.5	35.0	55.0	75.0
TEK	Divergent					
High	Le	R - L	2.0	20.0	35.0	60.0*
	Re	L - R	0.0	15.0	41.0	48.8
Low	Le	R - L	-3.0	13.5	39.0	48.8
	Re	L - R	-3.0	15.0	31.0	48.8
	Convergent					
High	Le	L - R	-1.5	15.0	26.0	51.0
	Re	R - L	-0.5	16.0	37.5	58.0
Low	Le	L - R	2.0	8.0	24.0	33.0
	Re	R - L	-1.0	8.0	22.0	40.0
HWM	Divergent					
High	Le	R - L	-1.0	18.5	42.0	60.0*
	Re	L - R	0.0	17.0	42.0	63.0*
Low	Le	R - L	6.0	11.0	27.0	51.0
	Re	L - R	0.5	13.0	31.0	49.5
	Convergent					
High	Le	L - R	-3.5	13.0	30.0	67.5*
	Re	R - L	-1.0	14.0	34.0	51.0
Low	Le	L - R	-4.0	7.0	21.0	30.0
	Re	R - L	-2.5	8.0	27.0	44.0
GSH	Divergent					
High	Le	R - L	4.0	21.0	46.0	48.8
	Re	L - R	4.0	22.0	40.0	48.8
Low	Le	R - L	6.0	17.5	35.0	48.8
	Re	L - R	7.0	18.0	34.0	48.8
	Convergent					
High	Le	L - R	-5.5	5.0	25.0	55.0
	Re	R - L	-2.5	4.0	22.0	46.0
Low	Le	L - R	-8.5	1.0	7.0	9.5
	Re	R - L	-9.0	-3.5	2.5	18.0
SCP	Divergent					
High	Le	R - L	2.0	20.0	42.0	58.0*
	Re	L - R	2.0	20.5	42.5	67.5*
Low	Le	R - L	3.5	11.0	23.0	51.5
	Re	L - R	8.0	19.0	28.0	59.0
	Convergent					
High	Le	L - R	-5.0	12.0	26.0	67.5*
	Re	R - L	-5.0	10.5	33.0	62.0*
Low	Le	L - R	-8.0	4.0	15.0	26.5
	Re	R - L	-7.5	6.0	22.0	36.5

*One neutral point only.

—Arbitrary value, no neutral point.

TABLE 2

DELAY OF ALTERNATE NEUTRAL POINT IN MSEC

Observer	Luminance	Vergence Category / Referent Eye	Movement (Upper Belt)	Referent Exposure Duration in Msec 12.5	35.0	55.0	75.0
TEK		Divergent					
	High	Le	R - L	52.5	41.0	56.0	60.0*
		Re	L - R	57.0	57.0	61.5	48.8
	Low	Le	R - L	43.5	55.0	60.0	48.8
		Re	L - R	53.5	59.5	61.0	48.8
		Convergent					
	High	Le	L - R	53.0	77.0	64.0	62.5
		Re	R - L	53.0	59.5	68.0	70.0
	Low	Le	L - R	52.0	59.0	60.0	68.5
		Re	R - L	55.5	71.0	73.0	87.0
HWM		Divergent					
	High	Le	R - L	55.0	60.0	63.0	60.0*
		Re	L - R	54.0	62.0	64.0	63.0*
	Low	Le	R - L	55.5	61.0	69.5	74.0
		Re	L - R	57.0	64.0	67.5	76.0
		Convergent					
	High	Le	L - R	53.0	59.0	69.0	67.5*
		Re	R - L	58.0	63.0	68.5	71.5
	Low	Le	L - R	62.0	66.0	70.5	85.0
		Re	R - L	58.0	65.0	75.0	81.0
GSH		Divergent					
	High	Le	R - L	57.0	62.0	68.5	48.8
		Re	L - R	61.0	68.5	54.0	48.8
	Low	Le	R - L	60.0	64.0	67.0	48.8
		Re	L - R	67.0	76.0	74.5	48.8
		Convergent					
	High	Le	L - R	42.0	47.0	61.0	71.5
		Re	R - L	55.0	60.0	72.0	75.0
	Low	Le	L - R	48.5	59.0	83.0	84.0
		Re	R - L	54.0	61.0	71.0	84.0
SCP		Divergent					
	High	Le	R - L	59.0	69.0	66.0	58.0*
		Re	L - R	58.0	54.5	66.0	67.5*
	Low	Le	R - L	60.5	69.0	77.0	84.5
		Re	L - R	47.0	67.0	77.5	75.5
		Convergent					
	High	Le	L - R	45.5	53.5	65.0	67.5*
		Re	R - L	53.0	54.0	62.5	62.0*
	Low	Le	L - R	48.0	54.0	73.0	74.5
		Re	R - L	51.0	49.0	67.5	70.5

*One neutral point only.

—Arbitrary value, no neutral point.

TABLE 3

OBSERVER MEAN DIFFERENCES FOR EQUIVALENT ILLUMINATION, "CONTROL" JUDGMENTS (N = 3)

Observer / Luminance	Vergence Category / Referent Eye	Movement (Upper Belt)	12.5 A/F	12.5 S/F	12.5 A/S	35.0 A/F	35.0 S/F	35.0 A/S	55.0 A/F	55.0 S/F	55.0 A/S	75.0 A/F	75.0 S/F	75.0 A/S
TEK	Divergent													
High	Le	R - L	0.7	1.3	0.3	1.7	1.7	1.3	1.3	2.0	1.3	2.0	1.7	2.0
	Re	L - R	0.3	-1.3	0.3	0.7	-0.7	1.0	1.3	1.7	1.7	1.3	1.7	1.0
Low	Le	R - L	0.3	1.0	1.0	0.7	1.7	1.7	1.0	1.7	1.0	1.0	1.0	2.0
	Re	L - R	-0.7	0.3	0.3	-0.3	0.0	0.7	0.0	-0.3	0.3	0.3	0.0	0.7
	Convergent													
High	Le	L - R	0.3	0.3	-1.3	0.0	1.0	-0.3	-0.3	0.0	-0.3	-0.3	-1.0	-0.3
	Re	R - L	0.7	0.3	1.3	0.7	1.0	1.0	0.3	1.0	0.7	0.0	1.0	1.0
Low	Le	L - R	2.0	0.7	0.3	1.7	0.7	0.7	1.0	1.0	0.0	1.0	0.3	1.0
	Re	R - L	1.3	1.7	2.0	1.3	2.0	1.0	1.0	1.7	2.0	2.0	1.7	1.7
HMW	Divergent													
High	Le	R - L	3.0	6.3	-2.3	4.7	5.7	-0.3	5.3	6.3	4.0	6.0	6.0	5.3
	Re	L - R	2.7	4.0	-3.3	4.0	5.3	-1.0	5.7	4.7	1.2	6.0	5.7	4.3
Low	Le	R - L	-5.0	2.5	-4.0	-3.3	4.7	-2.7	-0.7	5.0	-2.1	1.7	6.0	-1.0
	Re	L - R	-3.3	1.2	-3.7	-2.3	3.7	-3.0	-0.5	4.7	-1.2	1.0	4.7	-0.7
	Convergent													
High	Le	L - R	2.7	-3.3	4.0	-1.7	-3.3	3.3	-2.7	-4.0	0.0	-3.3	-4.3	-2.7
	Re	R - L	3.0	-2.3	6.3	-2.3	-4.3	4.0	-3.0	-4.3	0.2	-4.0	-4.0	-1.3
Low	Le	L - R	6.7	0.7	6.0	6.0	-0.7	5.3	5.0	-2.3	5.3	4.7	-3.3	3.7
	Re	R - L	6.0	2.3	5.3	4.7	0.0	4.7	6.0	-2.3	6.0	4.0	-3.3	2.8

(continued on next page)

TABLE 3 (cont)

OBSERVER MEAN DIFFERENCES FOR EQUIVALENT ILLUMINATION, "CONTROL" JUDGMENTS (N = 3)

Observer	Vergence Category		Referent Exposure in Msec and Experimental Manipulations												
Luminance	Referent Eye	Movement (Upper Belt)	A/F	12.5 S/F	A/S	A/F	35.0 S/F	A/S	A/F	55.0 S/F	A/S	A/F	75.0 S/F	A/S
GSH	Divergent														
High	Le	R - L	0.3	3.0	1.3	3.0	3.3	3.0	5.3	3.7	3.3	5.0	3.3	3.7
	Re	L - R	1.0	3.0	1.0	3.7	3.0	2.3	4.7	3.0	3.7	4.7	4.0	3.0
Low	Le	R - L	-1.0	2.3	0.3	0.0	2.0	1.3	0.3	2.7	2.3	1.0	3.0	2.0
	Re	L - R	-1.0	2.0	0.3	0.0	2.7	1.3	1.0	2.3	1.7	1.0	2.7	2.7
	Convergent														
High	Le	L - R	1.0	1.0	3.0	-0.5	-1.0	1.3	-1.0	0.7	1.7	-1.0	-1.0	0.7
	Re	R - L	0.3	1.3	3.0	-0.3	-0.3	2.0	-0.7	0.0	1.7	-1.0	-1.0	0.0
Low	Le	L - R	6.3	3.3	4.0	5.7	2.7	4.0	4.0	1.7	3.3	2.7	2.7	3.0
	Re	R - L	6.3	3.3	3.7	5.0	2.7	4.0	4.0	2.0	3.3	3.3	1.7	3.0
SCP	Divergent														
High	Le	R - L	2.3	4.3	-2.3	4.3	5.7	-2.0	4.3	4.7	3.0	4.7	4.7	3.2
	Re	L - R	3.0	4.7	-3.0	5.0	4.3	1.2	5.2	5.0	3.3	5.3	5.0	5.0
Low	Le	R - L	-3.3	2.7	-2.7	-2.5	3.0	-2.2	-2.0	3.3	-1.5	0.5	3.7	-1.5
	Re	L - R	-2.5	2.0	-1.2	-2.5	3.0	-1.8	0.8	3.7	-2.0	2.2	4.0	-0.8
	Convergent														
High	Le	L - R	3.0	-3.0	4.7	-1.7	-3.7	3.3	-4.0	-3.3	0.5	-3.0	-3.7	-1.8
	Re	R - L	2.3	-2.3	4.3	-1.8	-3.0	3.3	-2.3	-3.0	-1.5	-2.3	-3.2	-2.0
Low	Le	L - R	5.0	2.5	5.0	5.3	1.2	5.3	4.0	-2.2	3.7	4.3	-2.3	4.0
	Re	R - L	6.7	-1.7	4.3	4.7	-1.5	4.7	3.3	-2.0	4.0	3.0	-2.3	3.7

A/F - Constant 11.3% trans. filter with Bloch's Law equivalent filter.
S/F - Constant 12.5 msec exposure with Bloch's Law equivalent filter.
A/S - Constant 11.3% trans. filter with experimental exposures.